

# On the Nature of the X-ray Emission from the Galactic Center Region

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The origin of the X-ray emission from the central region of the Galaxy has remained a mystery<sup>1,2,3,4</sup>, despite extensive study over the past two decades. A fundamental question is the relative contribution of the point-source and diffuse components of this emission, which is critical to understanding the high-energy phenomena and processes unique to this Galactic nuclear environment. Here, we report on results from a large-scale imaging survey of the Galactic center with sufficient spatial resolution to allow a clean separation of the two components. The He-like Fe  $K\alpha$  emission, previously attributed to the diffuse emission<sup>1</sup>, is found largely due to the discrete X-ray source population. The number and spectrum of such sources indicate the presence of numerous accreting white dwarfs, neutron stars, and/or black holes in the region. The diffuse X-ray emission dominates over the contribution from the faint discrete sources and is shown to be associated with distinct interstellar structures observed at radio and mid-infrared wavelengths, suggesting that it arises from the recent formation of massive stars.

We have carried out a systematic X-ray survey of the Galactic Central (GC) region at arc-second scales with the *Chandra* X-ray Observatory<sup>5</sup>. Figure 1 presents the image of the X-ray emission arising from the GC region. The figure, though optimized to reveal low surface brightness features, shows many discrete sources. Our preliminary source detection analysis results in  $\sim 1000$  discrete sources in the field with a signal-to-noise of  $\gtrsim 3\sigma$ . Less than 20 of these sources are previously known objects, most of which are bright X-ray binaries<sup>6,7</sup>; examples include the two bright accreting X-ray binaries, 1E 1743.1-2843 and 1E 1740.7-2942. Based on a comparison with the source density in a relatively blank region of the Galactic plane<sup>8</sup>, we estimate that up to half of our newly detected sources could be luminous background active galactic nuclei, the X-ray radiation from which is highly attenuated by the Galactic interstellar absorption. The X-ray absorption also varies across the field, affecting the surface brightness distribution, particularly in the 1 – 3 keV

energy band. The majority of the detected sources are in the energy range of  $2 - 10$  keV with a luminosity range of  $10^{32} - 10^{35}$  ergs s $^{-1}$  at the distance of the GC.

We consider the nature of the large number of newly-detected X-ray sources by examining their composite spectral signature and compare this to the diffuse emission (Figure 2). The accumulated source spectrum (excluding the two brightest ones) within the central region shows a distinct emission feature centered at  $\sim 6.7$  keV with a Gaussian width of  $\sim 0.09$  keV, which agrees with previous measurements<sup>4</sup>. This spectral feature represents the He-like Fe K $\alpha$ -line. Modest contributions from the  $\sim 7.0$ -keV H-like Fe K $\alpha$ -line and the 6.4-keV fluorescent line of neutral to moderately ionized Fe atoms are also present in the spectrum. These emission lines are characteristic of X-ray binaries containing white dwarfs, neutron stars, or black holes, especially at relatively quiescent states<sup>9,10</sup>. This X-ray binary explanation is also consistent with the otherwise flat and relatively featureless shape of the spectrum. But other possibilities cannot be ruled out. The narrow emission lines (at  $\sim 2.4$  keV and possibly at other energies) are likely due to a relatively small contribution from massive stars. The X-ray spectrum of the luminous Arches star cluster<sup>11</sup>, for example, shows distinct narrow lines and is considerably softer than the mean source spectrum shown in Figure 2. The upturn of the source spectrum below  $\sim 2$  keV is a result of the contribution from relatively nearby sources, which suffers less amounts of soft X-ray absorption by the interstellar medium than the X-ray radiation from the GC.

Our survey also shows that large amounts of diffuse X-ray emitting material are distributed asymmetrically around the GC and are particularly concentrated in the region about  $10'$  to the lower left of Sgr A\* (Ref. 12; Figure 2). Several additional large-scale diffuse X-ray features are present in the soft band ( $1 - 3$  keV) around the Sgr A\*, some of which apparently extend into high Galactic latitude regions outside the field of view of the X-ray image. There are also prominent features associated with the Sgr C complex and near the Galactic microquasar 1E 1740.7-2942. The count rate ratio of the sources to the enhanced diffuse component in the two spectra (Figure 2) is  $\sim 0.25$  in the  $2 - 10$  keV band. Even in the regions of the deepest exposure ( $\sim 120$  ks in the Sgr B2 region, including an archival observation<sup>13</sup>), where the source detection limit reaches  $\sim 8 \times 10^{31}$  ergs s $^{-1}$ , the diffuse emission dominates. There is no known X-ray source population that might contribute substantially below this source detection limit.

The He-like Fe K $\alpha$ -line (at  $\sim 6.7$  keV) is not as prominent in the diffuse emission spectrum as in the discrete source spectrum. The ubiquitous and strong presence of this line in previous X-ray spectra of the GC region<sup>1</sup> is partly due to discrete sources. The reduced strength of the He-like

Fe line no longer requires the presence of large amounts of  $\sim 10^8$  K gas, which are very difficult to explain physically<sup>4</sup>. The weaker He-like Fe line as well as the prominent ion lines at lower energies (e.g., Si XIII  $K\alpha$  and S XV  $K\alpha$ ; Figure 2) are consistent with an optically-thin thermal plasma with a characteristic temperature of  $\sim 10^7$  K, comparable to that typically found in young supernova remnants. Such plasma still significantly contributes to the 6.7-keV line. One example is Sgr A East, most likely a young supernova remnant, which has an X-ray spectrum characterized by a thermal plasma with a temperature of  $\sim 2$  keV and shows a strong 6.7-keV emission line<sup>14</sup>.

Our spectral results also suggest that nonthermal processes contribute significantly to the diffuse X-ray emission, especially at the higher energies. A recent study has demonstrated that the inclusion of a non-thermal component in modeling the X-ray background spectrum from the Galactic plane and toward the GC significantly reduces the required characteristic temperature of the plasma component<sup>3</sup>. But the nature and origin of this contribution remain unclear. Nearly half of our detected diffuse emission in the 5-8 keV band is due to the Fe 6.4-keV line (Figure 2), which results from the filling of neutral to moderately ionized Fe K shell vacancy due either to ionization by hard X-ray radiation ( $> 7.1$  keV) or to collision with non-relativistic cosmic rays<sup>3</sup>. We find that the distribution of the line emission is indeed generally correlated with lumpy dense molecular material<sup>15,16</sup>. However, currently there is not a sufficient population of bright X-ray sources in the GC region to produce the 6.4-keV line fluorescence<sup>13,17</sup>. One possibility might be that the luminosity of X-ray sources (e.g., the GC supermassive black hole) varies greatly and that the currently low luminosity is abnormal. If the luminosity averaged over the light crossing time of the region (a few hundred years) is several orders of magnitude higher, much of the 5-8 keV band diffuse emission may then be explained as the past point-like emission scattered/fluoresced off molecular clouds found in the region<sup>18,15</sup>.

We also find that the continuum emission in the 4-6 keV range is substantially more uniformly distributed along the central Galactic plane than both the 6.4-keV line and the emission in the lower energy bands. This continuum emission may be induced partly by nonthermal electrons. However, we find little correlation between diffuse X-ray and radio features in the GC region. Of the eight prominent nonthermal filaments (NTFs) known, only one has a direct X-ray counterpart: G359.54+0.18 (Ref. 19; marked as “X-ray Thread” in Figure 1). In particular, the X-ray emission is not correlated with the most prominent NTFs in the Radio Arc or with the mid-infrared shells/arcs (e.g., Figure 3). This suggests that the bulk of the emission cannot be due to the

inverse Compton scattering of the cosmic microwave background or the interstellar infrared radiation off relativistic electrons<sup>20</sup>. But bremsstrahlung and Fe K shell vacancy from non-relativistic cosmic-ray electrons ( $\lesssim 1$  MeV) remain a possibility<sup>3</sup>.

Such multiwavelength comparisons have provided us with a new perspective of the interplay between various stellar and interstellar components in the GC region. The enhanced diffuse X-ray emission is globally correlated with massive star forming regions, which include the GC, Arches, and Quintuplet clusters<sup>21</sup>. In particular, the Quintuplet cluster is thought to be responsible for producing distinct shell-like structures as seen in radio and mid-infrared (Figure 3). These structures, together with the enclosed diffuse X-ray-emitting materials, are likely a product of mechanical energy release from massive stars in form of supernova explosions and fast stellar winds.

It is interesting to compare the massive star forming regions of the GC with the 30 Doradus nebula. The collective energy releases in the two regions are comparable<sup>21,22</sup>. With an overall extent of about 300 pc, the 30 Dor nebula consists of blisters of X-ray-emitting gas enclosed in photon-ionized loops and shells<sup>22</sup>. But the bulk of the X-ray emission arises in gas with a characteristic temperature  $\lesssim 10^7$  K, and the gas apparently cools off with increasing distance from the central cluster R136. However, such gas in the GC region is not traced by X-rays observed in our *Chandra* survey, because of the heavy foreground absorption ( $\sim 10^{23}$  cm<sup>-2</sup>). The strongly enhanced hard X-ray emission ( $\gtrsim 4$  keV) is thus very unique to the GC environment. The expansion and outflow of the high-pressure and buoyant plasma/cosmic rays may be responsible for the large-scale, vertical diffuse radio and soft X-ray features observed above and below this region of the Galaxy<sup>23,24</sup>.

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**Figure 1** — Mosaic image of the Galactic center region. This image covers a  $\sim 2 \times 0.8$  square degree band in the Galactic coordinates and is centered at  $l^{II}, b^{II} = -0.1^\circ, 0^\circ$ , roughly the location of the Sgr A Complex. The three energy bands are 1 – 3 keV (shown in red), 3 – 5 keV (green), and 5 – 8 keV (blue). The data consist of 30 separate pointings and were acquired during July 2001 with the front-illuminated Advanced CCD Imaging Spectrometer (ACIS-I). The spatial resolution ranges from  $\sim 0.5''$  on-axis to  $\sim 5''$  at the near edge of the CCD and to  $\sim 10''$  at the diagonal edge. This image is apertively smoothed with a signal-to-noise of 3. The intensity is plotted logarithmically to emphasize low surface brightness features. Standard imaging calibration and exposure-correction have been applied as well as corrections for the charge transfer inefficiency effects<sup>5,25</sup>.

**Figure 2** — Comparison of accumulated point source (lower) and diffuse emission (upper) spectra. These two spectra are extracted from an ellipse (with the major and minor axis equal to  $50'$  and  $12'$ ), centered at the Sgr A\* and oriented along the Galactic plane. Regions around two brightest sources (1E 1740.7-2942 and 1E 1743.1-2843) are excluded to minimize the spectral pile-up problem. The total count rate from these sources is comparable to that of the diffuse emission. For each spectrum, we derive an average auxiliary response, weighted by an image of selected events in the detector coordinates. The response is used for the channel energy scaling and for characterizing the spectral lines. A diffuse background, obtained in the outer field and normalized in both exposure and area, is subtracted from the two spectra.

**Figure 3** — A multiwavelength close-up of the recent massive star forming region near the GC. The color image, plotted also in the standard Galactic coordinates, is a composite of 20 cm radio continuum (red; Ref. 26);  $25\mu\text{m}$  mid-infrared (green; Ref. 16); and 6.4 keV line emission (blue).

